1996

Intellimotion

Keeping up with California PATH Research in Intelligent Transportation Systems

Automated Highway Systems

PATH Research in NAHSC

Steven Shladover
PATH

Since PATH was founded, ten years ago, our researchers have been working on Automated Highway Systems (AHS). Until the AHS program sponsored by the Federal Highway Systems Administration (FHWA) began in late 1993 (starting with the AHS Precursor Systems Analyses), PATH was doing the only AHS research in the United States, and probably in the world. PATH researchers participated in those 1993 studies, and PATH is now one of the Core Participants in the National Automated Highway System Consortium (NAHSC), which is conducting the System Definition Phase of the AHS program in partnership with the United States Department of Transportation. Our other partners in the NAHSC are: Bechtel, Caltrans, Carnegie-Mellon University's Robotics Institute, Delco Electronics, General Motors, Hughes, Lockheed-Martin, and Parsons-Brinckerhoff.

PATH faculty, graduate student, and staff researchers continue to follow many of the lines of research they have been pursuing under Caltrans' sponsorship for years. This research is now being augmented by our work as part of the NAHSC. Some research areas have expanded, and new ones have been introduced as well. This issue of Intellimotion concentrates on PATH's current NAHSC research, rather than the long-standing projects described in earlier issues.

SmartPath AHS Simulator Animation

Our broad experience in AHS issues makes it sensible for us to work in most areas of the NAHSC work plan. PATH roles within NAHSC currently include:

- Concept Definition – Task leader, concentrating on safety and throughput analyses and development of application scenarios;
- Enabling Technology Development – Research in lateral and longitudinal control, stereo vision for lane tracking and obstacle detection, and software safety/testing;
- Tools Development – Task leader, including development of system-level microsimulation, safety analysis methods, capacity prediction

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Magnetic Markers on I-15 Test Track for NAHSC Demonstration

Jürgen Guldner, Satyajit Patwardhan,
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An Automated Highway System (AHS) requires communication between individual vehicles, between the roadway infrastructure and vehicles, and possibly also between vehicles and the roadway infrastructure. This work concentrates on unidirectional communication from the roadway infrastructure to individual vehicles and discusses the test track preparation for the National Automated Highway Systems Consortium (NAHSC) demonstration on Interstate 15 near San Diego, CA, in 1997. For details, please refer to [1].

In the AHS scenario presently studied at California PATH, magnetic markers are used as references for lane keeping control [2]. The magnets are implanted in the road surface and measurements of vehicle lateral displacement from the magnets are used to automatically steer vehicles within the designated lane. Furthermore, magnetic markers have an excellent capability for binary coding using their polarity. "North pole up" is interpreted as a binary '1', "South pole up" as a binary '0'. Binary coding allows information to be transmitted from the roadway to a vehicle for utilization in all AHS subtasks. Similarly, human driving features information communication from the roadway to the driver: human drivers extract and exploit both explicit road information such as roadside signs, and implicit road information like upcoming road geometry during highway driving [3]. The selection of highway features to be communicated to AHS vehicles via binary coding of magnet markers on the I-15 test trackincludes:

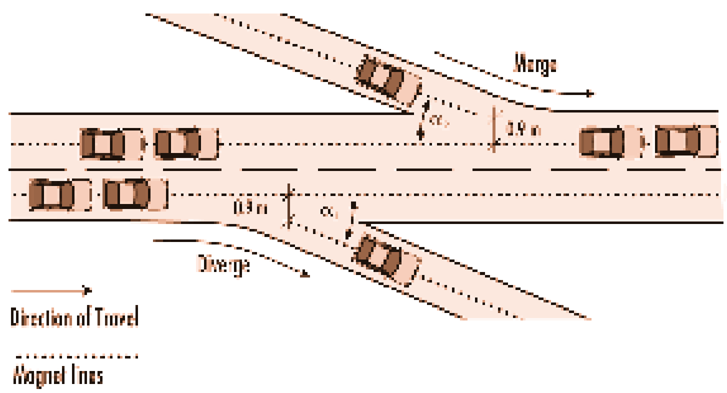

Figure 1: Merge and diverge situations on two through-lanes of a highway with two ramps at angles a_1 and a_2

Road geometry (curvature). Communicating road geometry to the vehicle motion control system is vital for safe AHS operation and, in addition, improves ride comfort. In particular, automatic steering feedback control design is one of the most challenging control subtasks within AHS and is significantly improved by preview of the upcoming road curvature, i.e. for utilization as feedforward control. This also improves ride quality, since US highways feature abrupt curvature changes without spiral transitions as are being used in Europe. Preview of upcoming curves allows lateral control to generate smooth transitions using anticipatory rather than reactive behavior, avoiding lateral jerks at curve beginnings and ends.

Merge/diverge for on/off-ramps. At on-ramps, a lane merges into a through lane. Conversely, at off-ramps, a lane diverges off a through lane to a ramp.

The magnet reference line of a merging lane terminates when the two lane centerlines approach within 0.9 m (approx. 3 ft.) to avoid interference of magnetic fields of adjacent magnets, see Figure 1. Lane diverges are constructed respectively, with the magnet line of the diverging lane commencing with a lateral offset of 0.9 m from the magnet line of the through lane.

Lane change. AHS requires the ability of vehicles to change lanes on multiple lane highways for traffic coordination, at intersections and at AHS entrances and exits. A lane change requires the vehicle to leave the magnet line, to cross over into the target lane using dead-reckoning, and to resume automatic steering control upon reaching the magnet line in the target lane. The desired crossover trajectory is usually defined as an S-curve with smooth curvature transitions to avoid lateral jerk, see Figure 2. In order to avoid changes of road curvature and to prevent missing magnet coding during a lane change, a number of areas with constant curvature and without any magnet coding were selected on I-15 as designated lane change areas.

Highway/lane/ramp identification. This code is used to identify highway lanes and ramps to AHS vehicles for navigation purposes, possibly in conjunction with a Global Positioning System (GPS). Lane and ramp information is also useful for coordination of vehicles, e.g. for lane change maneuvers as described above.

Other coded information specifies the magnet type being used, and communicates highway mile-posts to the vehicles. For future AHS implementations, additional road specific information could be incorporated into the coding. Typical examples are speed limits for certain stretches of the highway. Such information should be categorized into "permanent" and "variable" information. Permanent information, e.g. curvatures, can be "hard-coded" into the highway using magnet binary coding, very similar to conventional roadside signs and painted markings. Variable information such as temporary speed limits can be "soft-coded" by using permanent codes like highway identifications or mile-posts as placeholders for more specific information stored in maps and data files. Such maps and data files about highways could be up-dated frequently, or even transmitted to the vehicle on-line upon entry to the AHS. Electronic variable message signs are nowadays' equivalents of future information soft-coding.

Drilling for magnet placement

The NAHSC demonstration track is a stretch of I-15 near San Diego, CA, and comprises approx. 8 miles of two HOV lanes between the I-15 intersections with Route 163 (southern end) and Route 56 (northern end), see also [4]. Magnet installation on I-15 began with a ground breaking ceremony on June 28, 1996, under the supervision of Caltrans. The two HOV lanes are separated from the regular I-15 lanes by concrete barriers and entering/exiting is only possible at

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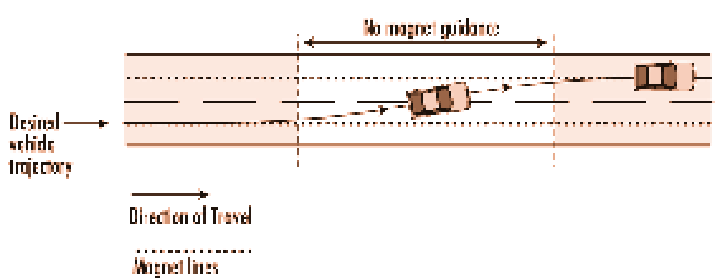

Figure 2. Lane change on an AHS highway

PATH Research Presentations

A list of some of the conferences or workshops where PATH sponsored research was or will be presented.

34 th IEEE Control and Decision Conference

New Orleans, Louisiana, December 1995

- *D. N. Godbole, J. Lygeros, E. Singh, A. Deshpande and A.E. Lindsey* "Design and Verification of Communication Protocols for Degraded Modes of Operation of AHS."

IFAC '96

San Francisco, California, July 1996

- *Datta N. Godbole, Farokh Eskafi and Pravin Varaiya* "Automated Highway Systems."
- *John Lygeros, Datta N. Godbole and Shankar Sastry* "Optimal Control Approach to Hybrid Systems Design."

35 th IEEE Control and Decision Conference

Kobe, Japan, December 1996

- *John Lygeros, Datta N. Godbole and Shankar Sastry* "A Verified Hybrid Control Design for Automated Vehicles."
- *John Lygeros, Datta N. Godbole and Shankar Sastry* "Multiagent Hybrid System Design Using Game Theory and Optimal Control."

3rd Annual World Congress on Intelligent Transport Systems

Orlando, Florida, October 14-18, 1996

- *Ching-Yao Chan* "Collision Analysis of Vehicle Following Operations in Automated Highway Systems."
- *Joy Dalhgren, Stein Weissenberger, Mark Hickman, and Hong Lo* "Lessons from Case Studies of Advanced Transportation and Information Systems."
- *Mark Hickman, Stein Weissenberger, and Joy Dahlgren* "Assessing the Benefits of a National ITS Architecture."
- *Jim Misener* "Application of Design and Evaluation Tools to the Automated Highway System."
- *Pravin Varaiya* (Moderator) Automated Highway Systems
- *James Bret Michael* (moderator) Vehicle Safety and Control
- *Joy Dahlgren* "Use of Case Studies for Short-term Projections of ITS Implementation."
- *Mark Miller* "Integrating Automated Highway Systems with Transit Operations."
- *Wei-Hua Lin* "Are the Objectives and Solutions of Conventional Dynamic User-equilibrium Models Always Consistent?"
- *Raja Sengupta* "Concept Definition of an Infrastructure-Supported AHS."
- *Stein Weissenberger* "Research and Testing Needs for ITS Deployment and Operation."
- *Steven Shladover* "Selection of Concepts for Automated Highway Systems."
- *Wei-Bin Zhang* "Minimal Reliability and Safety Requirements on AHS Vehicles for a Safe and Reasonably Efficient AHS."
- *Alexander Skabardonis* "Methodology for Estimating the Impacts of Incident Management Measures."
- *Mark Miller* "Integrating Automated Highway Systems with Transit Operations Within the Planning and Decision Making Processes at State, Regional and Local Levels."

ASME Congress and Exposition, Symposium on Transportation Systems

Atlanta, Georgia, November 17-22, 1996.

- *Seibum B. Choi* "The Design of a Control Coupled Observer for the Longitudinal Control of Autonomous Vehicles."

13th International Symposium on Transportation and Traffic Theory

Lyon, France, July 22-24, 1996

- *Carlos Daganzo* "The Nature of Freeway Gridlock and How to Prevent It."

INFORMS Fall 1996 Meeting

Atlanta, Georgia, November 4, 1996

- *Randolph Hall* "Traveler Information on a Capacitated/Dynamic Network."

ASME International Conference and Exposition

San Francisco, California, November 1995

- *T.J. Brosnihan, A.P. Pisano, R.T. Howe* "Surface Micromachined Angular Accelerometer with Force Feedback."

IEEE Solid-State Sensor and Actuator Workshop

Hilton Head Island, South Carolina, June 1996

- *M. Lemkin, B.E. Boser, D.M. Auslander* "A Fully Differential Lateral Sigma-Delta Accelerometer with Drift Cancellation Circuitry."
- *Thor Juneau, A.P. Pisano* "Micromachined Dual Input Axis Angular Rate Sensor."

IEEE Custom Integrated Circuits Conference

May 1996

- *M. Lemkin, B.E. Boser* "A Micromachined Fully Differential Lateral Accelerometer."

HOTCHIPS-VIII

Stanford, University, August 1996

- *B.E.Boser* "Surface Micromachining—An IC-Compatible Sensor."

1996 International Mechanical Engineering Congress and Exposition

Atlanta, Georgia, November 17-22, 1996

- *P.B. Ljung, A.P. Pisano* "Nonlinear Dynamics of Micromachined Rate Gyros."

IEEE International Conference on Control Applications

Dearborn, Michigan, September 15-18, 1996

- *Petros Ioannou (presentor), Houmair Raza, Bing Yang and Tom Xu* "Modeling and Control Design for a Computer Controlled Brake System."

NCGIA sponsored conference "Spatial Technologies, Geographic Information, and the City"

Baltimore, Maryland, September 9-11, 1996.

- *R.G. Golledge (presentor), J. Marston, and C.M. Costanzo* "The Impact of Information Access on Travel Behavior of Blind or Vision Impaired People."

Magnetic Markers

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either end. During normal operation, the two HOV lanes are open for rush hour traffic, southbound in the morning hours and northbound in the afternoon, and magnet installation work was restricted to night time. Since contrary to most highways, the lanes are being used bidirectionally, information coding was designed such that the NAHSC demonstration is feasible both in southbound and northbound directions.

We would like to express our sincere thanks to Lynn Barton, Vance Breshears, John Isaak, Joy Pinne, Jeff Scott, Frank Thomas, Randy Woolley and their Caltrans coworkers for their enormous efforts and the smooth cooperation during the planning and installation of the I-15 test track for the NAHSC demonstration in 1997.

References:

[1] J. Guldner, S. Patwardhan, H.-S. Tan, and W.-B. Zhang, "Coding of magnetic markers for demonstration of automated highway systems," in *Transportation Research Board Annual Meeting*, Washington, DC, USA (submitted), Jan. 1997.

[2] W. Zhang and R.E. Parsons, "An intelligent roadway reference system for vehicle lateral guidance/control," in *Proc. American Control Conf.*, San Diego, CA, USA, 1990 pp. 281-286.

[3] W. Zhang, "A roadway information system for guidance and control," in *Proc of Int. Conf. on Vehicle Navigation and Information Systems*, Dearborn, MI, USA, Oct. 1991.

[4] Ken Ellingwood, "Project begins to test 'driverless' freeway system," *Los Angeles Times*, p. A1/A22, June 28, 1996.

Will It Take Ultra-Reliable Vehicles to Make AHS Practical?

Wei-bin Zhang
PATH

Improved efficiency and safety are the two primary goals of an Automated Highway System, two goals that are sometimes at loggerheads. The safest system is not necessarily the most efficient, and vice versa. A recent PATH study investigates trade-offs between these goals, and suggests both safety and infrastructure design methods for achieving safety and efficiency.

The reliability of individual automated vehicles will greatly affect AHS efficiency and safety. Some studies have proposed "ultra-reliable" vehicles that use redundant technologies for vital add-on AHS functions. There is little doubt that such vehicles and their infrastructure can be designed using technologies developed for aerospace or commercial air traffic systems. However, the practicality of building and maintaining ultra-reliable vehicles at acceptable costs to users is questionable.

Our study considered a two-kilometer long single-lane AHS segment, physically separated from a conventional highway by barriers. Suppose that the Annual Average Daily Traffic (AADT) of this AHS segment is 20,000 vehicles (which represents the average current traffic volume of a single lane of Interstate 80 in the San Francisco Bay Area) and assuming that the failure rate of automated vehicles that follows an exponential distribution with $\lambda=10^{-4}$, the Mean Time Toward Failure of this highway segment (MTTF/lane) will be about 600 hours. A 10^{-4} failure rate for automated vehicles would mean that a vehicle being used two hours daily has a MTTF of 14 years. The MTTF/lane of 600 hours can be interpreted to mean that there would be an incident every 25 days on this AHS lane.

To prevent lane blockage, the AHS must either require highly reliable vehicles, to minimize the occurrence of blocked lanes, or the infrastructure must provide means to allow disabled vehicles to be removed from the traffic lane when failures occur.

We analyzed how reliable automated vehicles must be to make an AHS practical. Let us postulate that one tenth of California's nearly 4000 kilometers of interstate highways will eventually have one traffic lane accommodating AHS vehicles. Using the assumptions given in the above example, one of the 200 segments of this California AHS may be impacted by a failed vehicle at least once every 1.5 hours when the MTTF of vehicles is 10^4 hours. When the MTTF improves to 10^6 hours, the MTTF of this highway would be 12 days. Figure 1 shows the relationship between the MTTF of automated vehicles and the MTTF of the postulated California highway. It also demonstrates that when the AADT doubles, the MTTF of the highway is cut by 50%.

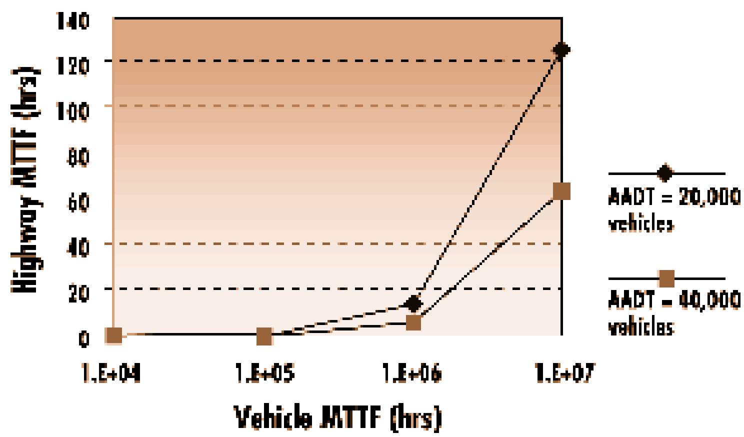

Figure 1. Relationship between MTTF of automated vehicles and MTTF of California AHS

It is almost certain that an automated vehicle with a MTTF of greater than 10^6 hours cannot be built at an affordable cost. It is doubtful that even a very small percentage of vehicles can be operated and maintained at a reliability level with an MTTF above 10^4. If we accept the fact that the AHS infrastructure and automated vehicles will occasionally fail, it is then important to look at what the consequences of failures will be, and how to enable the AHS to deal with them.

Can AHS be without ultra-reliable designs?

Since safety is a primary goal, when system failures do occur, it is necessary to prevent their resulting in fatalities and severe injuries. At least two design methods have been proposed to achieve this AHS safety goal, including:

- **Fail-safe control.** This strategy allows the system to detect failures and react to them in a predetermined manner so that adverse consequences can be avoided. 'Predetermined manner' could involve a vehicle being operated at a degraded mode (e.g., at a lower speed), being operated at increased distance from surrounding vehicles, or being stopped in order to avoid collisions. The cost of fail-safe designs can be significantly less than that of ultra-reliable vehicles. However when a fail-safe design is applied, the likelihood of the lane being blocked by a failed vehicle will be increased.

- **Vehicle operation policy:** Vehicle operation policy will determine both traffic speed and spacing between vehicles. It has been suggested that tightly spaced vehicles will have relatively low relative speeds when a collision occurs. Such an operation policy would reduce the impact of collisions, thus preventing injuries and fatalities. The trade-off, however, is an increased probability of low-impact collisions following a failure.

Since fail-safe designs may cause vehicles to overreact to non-vital failures, and since tight spacing policy may not allow a vehicle to have enough time to respond to rapid deceleration by the vehicle ahead of it, more frequent vehicle stalls and low-impact collisions may result. It is worth noting that the reduction in severity of incidents will also reduce the time required for clearing them up. Sensitivity analyses have been conducted to investigate "how much fail-safe" is enough, and the effects of adopting different safety designs and policies. However, it is certain that the AHS safety goal can be achieved using the above safety design methods. The question of efficiency remains:

How to improve AHS efficiency without compromising safety?

AHS efficiency will be determined not only by the reliability and safety of the vehicles, but to a great extent by infrastructure arrangements. Specifically, infrastructure arrangements can provide flexibility to keep vehicles taking fail-safe measures from blocking traffic. When a vehicle fails, several consequences may occur, including:

- the failed vehicle is operated at a degraded mode (lower speed) and is ejected at the next exit,
- the failed vehicle is controlled to a safe stop; and
- the failed vehicle collides with adjacent vehicles or the infrastructure and then comes to a crashed stop.

It is clear that all the above consequences, particularly the last two, will have a great effect on the efficiency of an AHS with a single lane configuration. This raises strong doubt about the practicality of such a configuration. To meet the minimum efficiency requirement, an AHS will demand an infrastructure arrangement that can bring a malfunctioning vehicle to rest without significantly affecting efficiency.

We investigated a two-lane AHS configuration, and determined that the probability of both lanes being blocked by failed vehicles is close to none ($< 12.5 \times 10^{-12}$ when vehicles are placed at an average spacing of > 15 meters) and that a two-lane AHS will, in the worst case scenario, still provide the designed throughput of a one-lane AHS. However, some early results indicate that initial implementation of an AHS consisting of more than one automated lane would be very difficult. At first, proposed AHS lanes will occupy traffic lanes on existing high-

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PATH’s Crucial Role in the Development of Automa

Jim Misener, PATH

Tucked in a corner of the University of California’s Richmond Field Station, and also in various corners of the UC Berkeley campus, UC Riverside, and the University of Southern California, a team of PATH researchers is developing a comprehensive suite of AHS tools. These mathematical models and simulations will provide the National Automated Highway System Consortium (NAHSC) with an objective basis to evaluate AHS concepts, then facilitate translating them into designs. All aspects of AHS are being modeled — from vehicles and control systems, to traffic flows, travel demand, and highway configurations.

The NAHSC tools development effort, led by PATH, is necessarily multidisciplinary and multiorganizational. Teammates from the other NAHSC partners are substantial contributors, but the centerpiece of the tools task — development of an AHS microsimulation — is being orchestrated at the Richmond Field Station. The overall effort began in March 1995 and will conclude in July 1998.

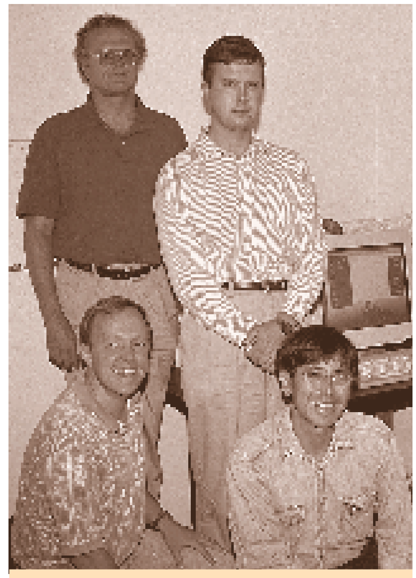
How Will Tools Be Used?

Three roles will be involved in applying the tools: that of the tool developer, the concept designer, and the AHS evaluator — all interacting continuously. The tool developers and concept designers collaborate to model the design in terms of the input parameters; this may entail the use of additional tools as prefilters to process the design, and it may also entail modification of the evaluation tool. The evaluators choose the performance metric to be analyzed, and picks an evaluation tool.

As an exampleof the differences between these roles, suppose that a concept designer is developing a platooning AHS concept. The concept designer wants to determine the regulation layer feedback control laws that govern vehicle dynamics within join, split, and lane change activities. The tool developer then offers a microsimulation tool to determine the efficacy of his control parameters.

On the flip side, suppose an AHS evaluator desires to analyze the capacity of a platooning AHS concept and chooses a throughput metric. The tool developer then offers a throughput evaluation tool that requires time and space utilization parameters for the same join, split, and lane change activities that the concept designer is concerned with. The evaluator can also use the microsimulation tool, this time to determine the time and space requirements to execute the platoon coordination layer maneuvers.

A top-level snapshot of the process, given from an evaluator’s point of view and showing the interrelationships among designs, scenarios, performance metrics and tools, is provided in Figure 1. In es-



Some members of the “tools” group (standing from le
Mark Miller, Daniel Wiesmann (sitting, from left) Bret

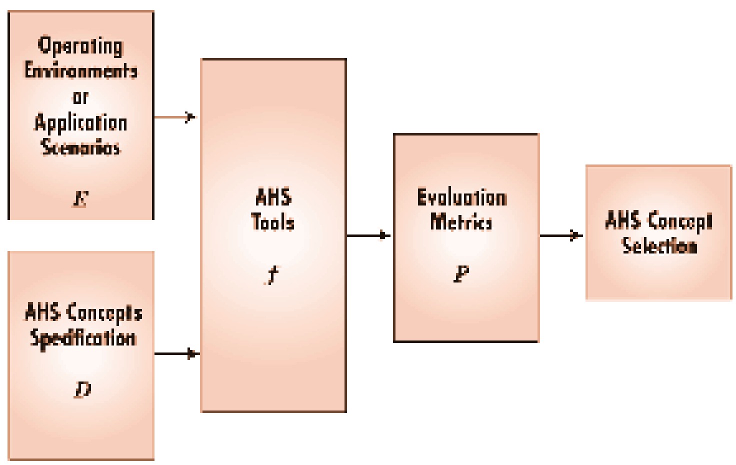


Figure 1. AHS Evaluation Framework

sence, once an AHS design, environment and performance metric are specified, one or several tools may be used to evaluate the performance of the design. Symbolically, if D stands for design, E for environment, and P for performance metric, all formally specified, then an appropriate tool evaluates the functional relationship,

$$P = f(D, E)$$

l Highway System Tools

ngola, Michael Kourjanski, Raja Sengupta, Datta Godbole, Misener, Farokh Eskafi

AHS Tools

There are over twenty ongoing AHS tool development efforts, organized into four subtasks—simulation tools, analysis and evaluation tools, CASE tools, and decision support tools. PATH is leading many and is involved in all. *Intellimotion 5.1* (1996), a special issue on modeling and simulation, provides an excellent primer on precursor PATH modeling work to the current AHS efforts. To describe each tool — or even the tool development that PATH is leading — would take several more issues. The time and space available now allows us to summarize only a few.

SmartAHS Tool

SmartAHS will be a full functionality microsimulation of all aspects of AHS. It will simulate vehicle dynamical behaviors under various control laws, roadway configurations, and geometries. Local, link, and network impacts can all be investigated using SmartAHS.

SmartAHS is a general purpose hybrid systems simulator for user-defined AHS architectures. SmartAHS models are specified using the Hybrid Systems Tool Interchange Format (SHIFT) programming language rather than traditional languages such as C or C++. SHIFT is a high-level language invented for SmartAHS development but generalizable for any specification of data and process models in terms of dynamic networks of hybrid systems. With SHIFT, AHS-specific models for highway layout, vehicle dynamics, actuators, sensors, and controllers can be written and simulated as objects in SmartAHS.

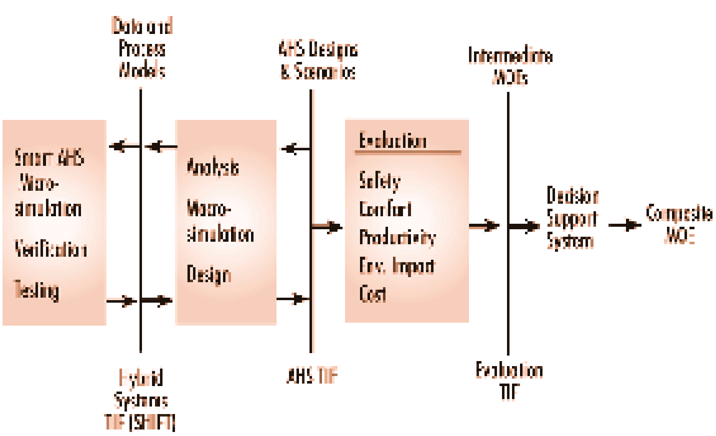


Figure 2. Relationship between the Hybrid Systems TIF, AHS TIF and Evaluation TIF

SmartAHS tools will contain a library of models written in SHIFT. These are provided so that different AHS designs can be simulated by mixing and matching combinations of these models; alternatively, the user may enter his or her own libraries of models. The SHIFT compiler and SmartAHS run time simulator is currently in alpha release.

The SmartAHS input and outputs are done by way of the SmartAHS Tool Interchange Format (TIF). The TIF is specified in three segments, illustrated in Figure 2: the Hybrid Systems TIF (or SHIFT), for detailed control architecture design; the AHS TIF, for AHS concept design and evaluation; and the Evaluation TIF (or Eval TIF), for performance metric or specification compliance evaluation.

By specifying SmartAHS inputs and outputs in this manner, various degrees of user sophistication are accommodated. Using a previous example, the concept designer can write control laws at the Hybrid Systems TIF level; either the concept designer or AHS evaluator can work at the AHS TIF level to determine unconditioned tool outputs; and finally, the AHS evaluator can work at the Evaluation TIF level to aggregate performance metrics according to his or her utility function.

SmartAHS requires the following inputs to run a simulation:

- Detailed design description including vehicle models, infrastructure models, operating rules and design failure events.

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Societal and Institutional Issues of Automated Highway Systems

Mark Miller
PATH

The National AHS Consortium has the mission of specifying, developing, and demonstrating a prototype automated highway system. However, the AHS program is not just a technical program. It has been correctly referred to as a socio-technical program, since it must address not only the technical issues associated with deploying, operating, and maintaining an automated highway system, but numerous societal and institutional issues as well. Two of these issues, now under investigation at the California PATH Program, are how to integrate the national AHS effort with planning and decision-making processes at the level of State Departments of Transportation and regional Metropolitan Planning Organizations, and how to integrate transit operations with AHS.

Planning and Decison-Making at State, Regional, and Local Levels

Successful implementation of automated highway systems will need to be tailored to local and regional transportation needs and priorities. The planning and development of successful AHS must be national in scope, yet flexible enough to be tailored and adaptable to transportation goals, objectives, and requirements at the state, regional, and local government levels where such systems will be implemented. In particular, an automated highway system must be adaptable enough to fit the planning and decision-making processes at the metropolitan planning organization and State Department of Transportation levels. How these processes work at these diverse institutional levels must be understood to determine the appropriate fit. Guidance derived from the Intermodal Surface Transportation Efficiency Act (ISTEA) regarding the use of federal funds through the Major Investment Study process recognizes the need for local control to meet local need. Thus, for a successful implementation, AHS will need to be tailored to the local and regional transportation needs and priorities. Planning and decision-making mechanisms will likely be different within each organization or group of organizations. General concerns at these different institutional levels are under investigation, and recommendations for addressing these concerns will be developed.

Numerous interviews, conversations, and focus groups involving representatives from many governmental organizations at the local, regional, and state levels have been and will continue to be conducted in the current and ongoing effort to better understand the concerns and priorities of governmental organizations at all levels about automated highway systems, and to develop recommendations for addressing them. Issues that have been identified include those of funding, operations, maintenance, regulation and enforcement of laws associated with system access, tort liability, deployment paths, means of mainstreaming AHS within Intelligent Transportation Systems (ITS), finding the means of integrating AHS within the overall planning process and conforming with the guidelines of ISTEA, the interface between an AHS and surrounding roadways, and risk of embarking on a new venture with no guarantee of counterbalancing benefits. These issues are not unique to governmental organizations and other public agencies: there would certainly be overlap with other stakeholders. How some of these issues could be addressed depends on how an AHS is described, both from system architecture and functional design points of view. Currently a multitude of potential AHS attributes are undergoing investigation and analysis to help form a foundation from which such issues can be addressed.

While automated highway systems are part of the much larger set of intelligent transportation systems, AHS is usually considered in the context of the most futuristic or long-term implementations. Just as ITS should generally be seen as a natural extension of the current transportation environment, as offering a toolbox of solutions to transportation-related problems, it is important that AHS be seen as a natural extension of the more "conventional" aspects of ITS. The mainstreaming of ITS within the conventional, more low-tech transportation environment will be an important determinant of its success. Similarly, the mainstreaming of AHS within the ITS world will be an important determinant of the success of AHS.

Transit Operations

Transit gives AHS the opportunity to meet the needs of people and markets not well served by the automobile. The integration of transit vehicles into the set of automated vehicle types has the potential for significant benefits in such roadway transportation problem areas as congestion, safety, air quality, and fuel consumption, as well as in addressing social equity, land use, and environmental considerations regarding AHS. Transit applications also offer the opportunity to demonstrate advanced technologies with a cadre of trained drivers. The focus of PATH's research is on developing ways to integrate automated highway systems with transit operations. A concept of AHS-based transit operations is under study to explore how specific transit systems might benefit from using a variety of AHS-based concepts. We are also examining several US transit systems where different concepts of vehicle/highway automation for transit are being developed, as these systems are considering the possible advantages of automation for current and future operations.

Transit-related aspects of ITS are tied to more immediate transit improvements. City buses are becoming mobile platforms for ITS in urban areas across the US, because the USDOT initiative to encourage intelligent transportation infrastructure investment in the transit industry is focused on "Smart" buses. Managers will soon know where "their bus" is – as they have known for years where their rail vehicles are – as automatic vehicle location technology is rapidly put into practice to assist bus fleet operations. Equally important for transit, customers may also soon know where their buses are. Many improved approaches to better inform customers of available service are being tested in the transit industry, e. g. Smart Kiosks, personal digital assistants, and microcellular telephones. These efforts to deploy an intelligent transportation infrastructure will lead to much more flexible and customer-responsive transit services. As these developments become successful, the increased volume of business will require a much improved supporting trunk line service. This is one area where it will be important for transit to take advantage of AHS technologies as they become proven.

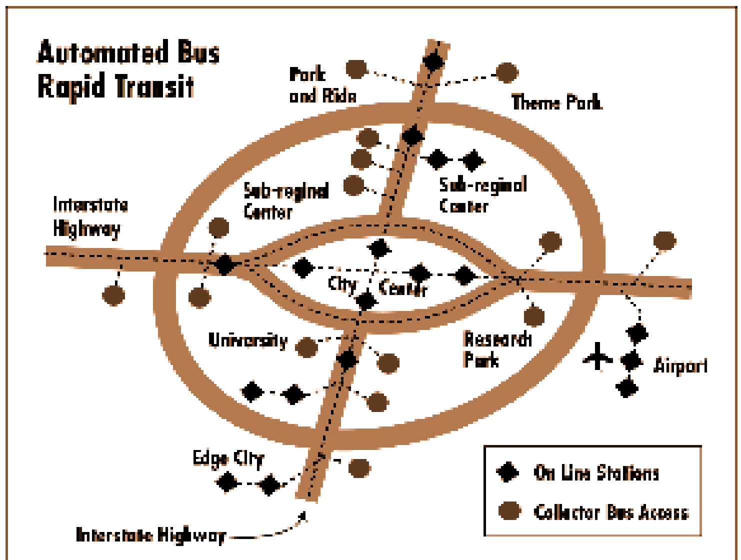

Figure 1. Flexible Transit Alternative. Buses operate in automated mode on own right-of way between major destinations, manually on surface streets.

Mechanically guided and coupled rail systems now operate automatically with high precision, but are expensive and difficult to retrofit into the land-use patterns of many of our urban areas. The AHS element of the ITS program offers great potential for transit, particularly the electronic guidance that will operate the automated highways of the future. Some effort has been given to electronic guidance for buses in Europe, and there are some possibilities for applying electronic guidance to buses in the US. The development of low-floor buses, hybrid electric power systems, and the new information infrastructure together are pointing the way. AHS opens an opportunity to plan new transit service with the

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PATH's Crucial Role

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- Scenario descriptions including highway configuration, traffic intensity, weather conditions and traffic events.

SmartAHS produces the following outputs:

- State trajectories of simulation entities (e.g., time profiles of vehicle positions, speeds and accelerations).
- Quantitative design parameters required by other analysis tools (e.g., time and space utilized during coordination maneuvers).
- Performance metrics as functions of state trajectories (e.g., throughput and emissions)

SmartCap Tool

SmartCap is a mesoscale simulator for studying AHS capacity, primarily intended to provide AHS concept discrimination in the area of throughput before SmartAHS becomes available. The tool allows the user to specify the highway configuration by connecting sections of the highway consisting of contiguous lanes. The simulator evolves vehicle flows according to conservation and velocity dynamics laws. It keeps track of different flow types, where flow types are distinguished by vehicle class (e.g., light-duty passenger vehicle) and by the exit to be taken by the vehicle. The model is intended to capture the basic capacity impact of vehicle control laws, abstracted through activities, and to capture secondary effects such as queuing, bottlenecks in a system due to exit or entrance, effects of lane change, and imbalance of density among lanes.

Safety Tools

A suite of Safety Evaluation Tools is under development to address deterministic and probabilistic consequences of collision (e.g., varying braking rates) resulting from safe spacing policies. These have recently been supplemented by obstacle avoidance and lane change maneuver tools. The final set of safety analysis tools will range from two-vehicle separation spacing analysis tools through multilane, multiple-vehicle microscale modeling.

Future AHS Tool Applications

Future AHS tool applications will address issues where significant quantitative modeling is expected to yield concept and design discriminators. Several of these applications will begin soon, with successive design and evaluation iterations expected to continue through deployment. Some applications include:

AHS Technologies

- Impact of communication delay, interference, and error rate on AHS operation
- Impact of sensing frequency and error on AHS operation
- Robustness of vehicle control algorithms against vehicle individuality, changing roadway conditions, and changing vehicle conditions, (e.g., tire/roadway friction, vehicle weight, and grade)

AHS Traffic Control

- Dynamic traffic assignment for throughput maximization subject to stringent exiting requirements
- Entry metering

AHS Safety

- Intervehicle spacing under various conditions: weather, road, lighting, communication, mixing
- Fault tree analysis for failure rate prediction and optimization
- Collision type, probability, and severity
- Collision prevention, (e.g., coordinated braking, coordinated lane changing)
- Subsequent collisions after an initial (and particularly, intraplatoon) collision
- Emergency response and handling
- Check-in or monitoring requirements
- Accident reconstruction and actuarial studies

AHS Capacity

- Capacity prediction under normal and abnormal driving conditions: weather, lighting, road surface conditions
- Capacity reduction due to incidents/accidents, as a function of vehicle/system response strategy

AHS Environmental Impact

- Combustion emissions
- Noise
- Energy Usage

continued next page

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Impacts on the Transportation System

- Interface with non-AHS roadways: mixed traffic, onramps and offramps
- Effect on traffic of local streets, especially central business districts
- Modifying city street configuration
- Delay reduction
- Trip reliability
- Comparison to alternatives: AHS vs. no action vs. other concepts and approaches to traffic congestion reduction

Summary

The NAHSC "toolbox" will continue to evolve as the needs and tool-use experience of users, including AHS stakeholders, dictate. The NAHSC concept evaluation and design tasks will be greatly aided by this growing suite of AHS tools, especially with the advent of SmartAHS, inclusion of AHS-local and regional impact models, and the development of increasingly high-fidelity sensor, communications. and highway design modules. And the PATH researchers, tucked in their respective corners, will certainly have a pronounced impact on the form of our future AHS.

Ultra-Reliable Vehicles

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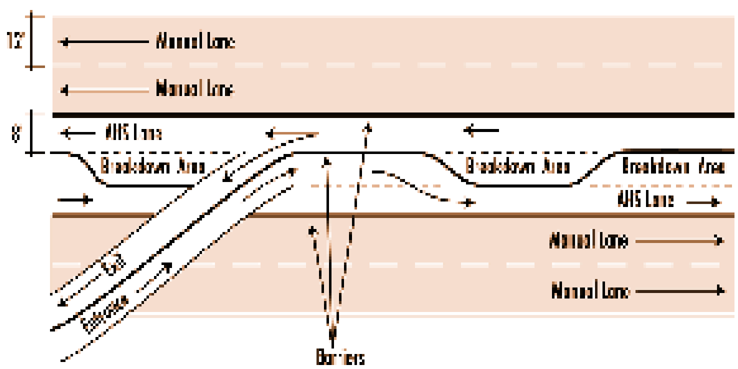

Figure 2. One-lane AHS with shared elevated entrance/exit and breakdown

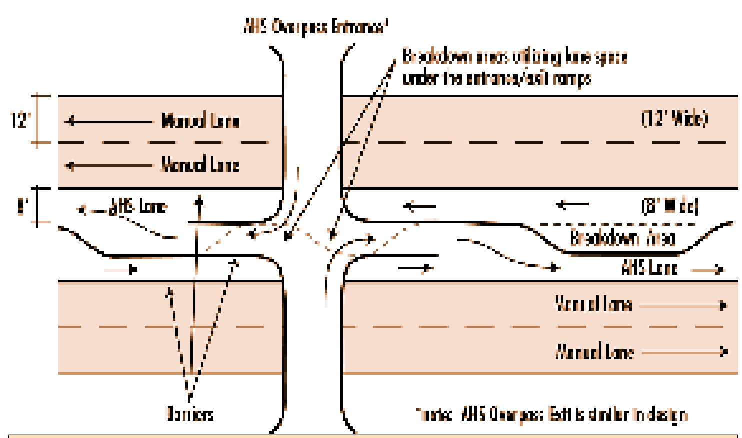

Figure 3. One-lane AHS with shared overpass entrance/exit and breakdown

ways, unless infrastructure expansion or new additions are available. Because the implementation of AHS will likely require that the infrastructure be ready prior to significant growth of the automated vehicle population, there are uncertainties in the level of occupancy of AHS lanes during the initial implementation stage. These uncertainties, plus the limitation in land use, will likely limit the scale of the initial implementation of AHS. Therefore, initial AHS infrastructures may only be implemented in heavily congested areas, where few lanes can be accommodated.

Our study proposed an alternative infrastructure design that incorporates a single AHS traffic lane for each direction, with a multipurpose lane in between. The multipurpose lane will not only accommodate disabled vehicles from traffic in both directions, but also serve as entrances and exits. Figures 2

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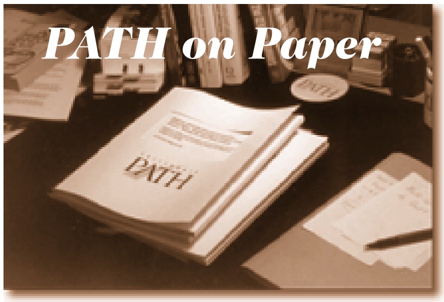

Below is an update on some recent PATH publications. A price list that includes research reports, working papers, technical memoranda, and technical notes can be obtained from the:
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Abstracts for all PATH research publications can be obtained via the PATH World Wide Web home page on the internet: *http://www.path.berkeley.edu*

PATH Research Papers

UCB-ITS-PRR-96-19, Modeling and Simulation of the Automated Highway System, Farokh H. Eskafi, July 1996, $20.00

UCB-ITS-PRR-96-20, Evaluation of the I-110 Corridor Smart Card Demonstration Project, Genevieve Giuliano, James E. Moore II, July 1996, $25.00

UCB-ITS-PRR-96-21, Commuters' Normal and Shift Decisions in Unexpected Congestion: En Route Responses to Advanced Traveler Information Systems Volume 2, Amalia Polydoropoulou, Moshe Ben-Akiva, Asad Khattak, Geoffrey Lauprete, July 1996, $33.00

UCB-ITS-PRR-96-22, A Comparison of Traffic Models: Part 1, Framework, Hong K. Lo, Wei-Hua Lin, Lawrence C. Liao, Elbert Chang, Jacob Tsao, August 1996, $15.00

UCB-ITS-PRR-96-23, Hierarchical, Hybrid Control of Large Scale Systems, John Lygeros, September 1996

UCB-ITS-PRR-96-24, Travel, Emissions, and Consumer Benefits of Advanced Transit Technologies in the Sacramento Region, Robert A. Johnston, Caroline J. Rodier, September 1996

UCB-ITS-PRR-96-25, Fault Detection and Identification with Application to Advanced Vehicle Control Systems: Final Report, Randal K. Douglas, Jason L. Speyer, D. Lewis Mingori, Robert H. Chen, Durga P. Malladi, Walter H. Chung, September 1996

UCB-ITS-PRR-96-26, Analysis, Design and Evaluation of AVCS for Heavy-duty Vehicles, Diana Yanakiev, Ioannis Kanellakopoulos, September 1996

PATH Working Papers

UCB-ITS-PWP-96-7, AHSCAP Dynamic Traffic Assignment Program User's Manual and Design Description, Bruce Hongola, June 1996, $10.00

UCB-ITS-PWP-96-8, Research and Testing for ITS Deployment and Operation, Stein Weissenberger, Joy Dahlgren, Mark Hickman, Hong Lo, July 1996, $5.00

UCB-ITS-PWP-96-9, Lessons from Case Studies of Advanced Transportation and Information Systems, Joy Dahlgren, Stein Weissenberger, Mark Hickman, Hong Lo, July 1996, $5.00

UCB-ITS-PWP-96-10, Assessing the Benefits of a National ITS Architecture, Mark Hickman, Stein Weissenberger, Joy Dahlgren, August 1996

UCB-ITS-PWP-96-11, Design, Modeling and Control of Steering and Braking for an Urban Electric Vehicle, Dragos Maciuca, August 1996, $10.00

UCB-ITS-PWP-96-12, Dynamic Traffic Assignment for Automated Highway Systems: A Two-lane Highway with Speed Constancy, Jacob Tsao, August 1996, $10.00

UCB-ITS-PWP-96-13, TravInfo Evaluation: Value Added Reseller (VAR) Study Phase 1 Results, Dimitri Loukakos, Randolph Hall, Stein Weissenberger, Y.B. Yim, August 1996, $10.00

UCB-ITS-PWP-96-14, TravInfo Evaluation: Institutional Element Phase 2 Results, Randolph Hall, Dimitri Loukakos, Stein Weissenberger, Y.B. Yim, August 1996, $10.00

Ultra-Reliable Vehicles

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and 3 (p. 13) show possible arrangements for this design. Assuming that the AHS lane width is 3.6 m and the barriers for physically separating traffic lanes are 1.8 m (0.6 m each), the total cross section of AHS lanes will be 12.6 m. This is about as wide as three of today's freeway lanes. Analysis shows that this alternative infrastructure design, combined with fail-safe system designs, will provide maximum design throughput under incident situations and minimize the amount of space occupied by AHS. Therefore, both safety and efficiency can be ensured.

This study concluded that an AHS can be developed using automated vehicles with reasonable reliability and infrastructures which can accommodate failed vehicles without affecting traffic on AHS lanes

Further study will investigate system operation aspects, and trade-offs between infrastructure and land use costs.

Societal and Institutional

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positive features of rail, but with greater flexibility and lower cost. Buses would operate, individually or in platoons, at close intervals but without bunching, and at level loading platform stops. They would operate on or off the automated highway lanes to efficiently link to our developing land use patterns in urban areas.

One vision of automated transit includes buses operated automatically on special lanes of the highway system, and operating under manual control to and from those automated sections. Automated operations would consist of automatic electronic guidance for the buses. This innovation would free transit from mechanically guided systems, with their very high inherent cost and rigid architecture. With transit guided electronically, designers could plan less costly and more flexible line haul and feeder systems. Such systems would be logical extensions of the direction transit is already headed within ITS. The eventual result may be an automated vehicle system that resembles light rail, but with neither rails nor trains. For example, several bus lines operating route deviation services could merge into one automated line at the entrance of a major freeway serving a downtown. The merge point itself could be a subregional activity center, and the link from downtown to the subregional center could be via AHS.

Such a "bus rapid transit system" could offer the performance features of rail transit at substantially

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PATH Research in NAHSC

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analysis methods, etc., as described in Jim Misener's article, on page 8;

- 1997 Automated Highway System Prototype Demonstration – Leader of development of fully automated platoon of vehicles and magnetic reference/ sensing system for use by multiple vehicles;
- Societal and Institutional Evaluations – Leader of transit application studies, as described in Mark Miller's article on page 10

Most of these activities grow out of years of PATH research, but acquire new significance when conducted in collaboration with other organizations of differing backgrounds and capabilities, as part of the NAHSC. For example, SmartAHS, the primary microsimulation tool PATH is developing for NAHSC, is a general-application version of SmartPATH, which has been used for several years at PATH to study automated vehicle operations based on specific assumptions. The platoon of Buick LeSabres General Motors has supplied for the 1997 AHS prototype demonstration, for which PATH is developing the control software, coordination protocols, magnetic marker sensing and throttle actuation systems, also includes brake actuation systems from Delphi Chassis (GM/Delco), steering actuation systems from Saginaw Steering (GM), communication systems from Hughes, and ranging radars and human/machine interfaces from Delco. This project is an exceptional opportunity for PATH researchers to integrate their work closely with that of industry leaders. The article by Jüergen Guldner, Satyajit Patwardhan, Han-Shue Tan, and Wei-Bin Zhang on page 2 describes one specific aspect of the demonstration development, in which roadway geometry information is encoded in permanent magnets installed in the roadway.

Other projects, particularly in the Concept Definition area, are new activities specific to the NAHSC program. Here, PATH researchers are looking at the attributes that characterize an automated highway system, and evaluating how those attributes influence the safety, throughput, costs, and deployability of the AHS. Wei-Bin Zhang's article on page 6 looks at how AHS infrastructure and vehicle operation policies can affect the goals of safety and efficiency.

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lower cost. Capital costs would be reduced where the line haul is on shared automated lanes, and the vehicle system would be smaller and lighter, therefore lowering structural costs. The design approach would be flexible: transit improvements could be made to fit the community served, rather than force-fitting the developing community to the architecture of the transit system. Such an automated bus rapid transit system would be ideal for a typical city with a beltway around the urban area, and interstate highways along radial routes from the downtown core.

Even though such vehicles would operate manually while on the existing street and highway system, their exact location would be monitored by an automated vehicle location system. Bus entry and circulation throughout the automated system would be well coordinated and communicated to customers. For better overall system performance, adjustments for demand shifts and incidents would also be made. Drivers would be freed to operate additional services, focus on customer service, or monitor safety concerns, depending on service priorities.

A schematic of what this flexible transit alternative could look like is shown in Figure 1 (p. 12). Here, the online stations are depicted with diamonds in such major trip generator locations as the city center, the university, the airport, a major subregional center, and an edge city. In those locations, the Automated Bus Rapid Transit would operate branch line service on its own grade separated right-of-way. In other lower-volume locations, buses would operate manually on the local street and highway system until they reach appropriate points, which appear as circles on the diagram, to access the automated system .

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